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EFFECT OF TRANSFORMER OPERATING CONDITIONS ON THE WEIGHT OF A 375-KILOWATT-ELECTRIC RANKINE CYCLE SPACE POWER SYSTEM

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • OCTOBER 1970

1. Report No. NASA TM X-2122	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle EFFECT OF TRANSFORMER OPERATING CONDITIONS ON THE WEIGHT OF A 375-KILOWATT-ELECTRIC RANKINE CYCLE SPACE POWER SYSTEM		5. Report Date October 1970
		6. Performing Organization Code
7. Author(s) Dale W. Cooper and John W. Stoll		8. Performing Organization Report No. E-5815
		10. Work Unit No. 120-27
9. Performing Organization Name and Address Lewis Research Center National Aeronautics and Space Administration Cleveland, Ohio 44135		11. Contract or Grant No.
		13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

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17. Key Words (Suggested by Author(s))		18. Distribution Statement
Transformer	Rankine cycle	Unclassified - unlimited
Efficiency		
Weight		
Power		

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	12	$3.00

*For sale by the Clearinghouse for Federal Scientific and Technical Information
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EFFECT OF TRANSFORMER OPERATING CONDITIONS ON THE WEIGHT OF A 375-KILOWATT-ELECTRIC RANKINE CYCLE SPACE POWER SYSTEM

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SUMMARY

An analytical study was performed to determine the optimum transformer operating temperature that results in minimum total system weight for a 375-kilowatt-electric (kW_e) Rankine cycle space power system. The load was considered to be a 375-kW_e ion thruster, while the power source was a 2-megawatt-thermal (MW_t) fast nuclear reactor driving a homopolar inductor alternator. There were four system radiators at 150°, 740°, 920°, and 1200° F (70°, 390°, 490°, and 650° C). Transformer weights and efficiency as a function of temperature were found from existing and calculated designs and scaled to 375-kW_e. A rectifier system was also employed, and various direct and refrigerated heat rejection systems to the four radiators were considered for both the transformer and rectifier.

The results show that minimum system weight occurred at a 740° F (390° C) operating temperature and that direct pumped fluid heat rejection gave the lowest weight. When the rectifier was operated at 150° F (70° C), minimum system weight also occurred with direct heat rejection to the 150° F (70° C) radiator. The tradeoff between transformer efficiency and specific weight was analyzed in the temperature range of 150° to 1200° F (70° to 650° C) for this space power system.

INTRODUCTION

At Lewis Research Center a research and technology program is being conducted on a 2-MW_t fast nuclear reactor Rankine space power system capable of producing 375 kW_e.

A complete system study has been performed from the reactor to and including the 1600-hertz homopolar generator (ref. 1). Four radiators at 150°, 740°, 920°, and 1200° F (70°, 390°, 490°, and 650° C) were employed, and weights of all subsystems are given. The complete system weighs 59.4 pounds per kW_e (27.0 kg/kW_e). The 480-volt line to neutral three-phase alternator has been designed for 375-kW_e output. This system is called a "nominal 300-kW_e system." The excess design power is intended to compensate for the overestimate in performance and the underestimate in weight that system studies usually yield.

One of the uses of high power nuclear systems is for deep space missions where electron-bombardment ion thrusters could be used for propulsion. Since high direct-current voltages are required for the thruster, additional power conditioning equipment is required. A transformer and a solid state rectifier are the additional power conditioning equipment considered in this study.

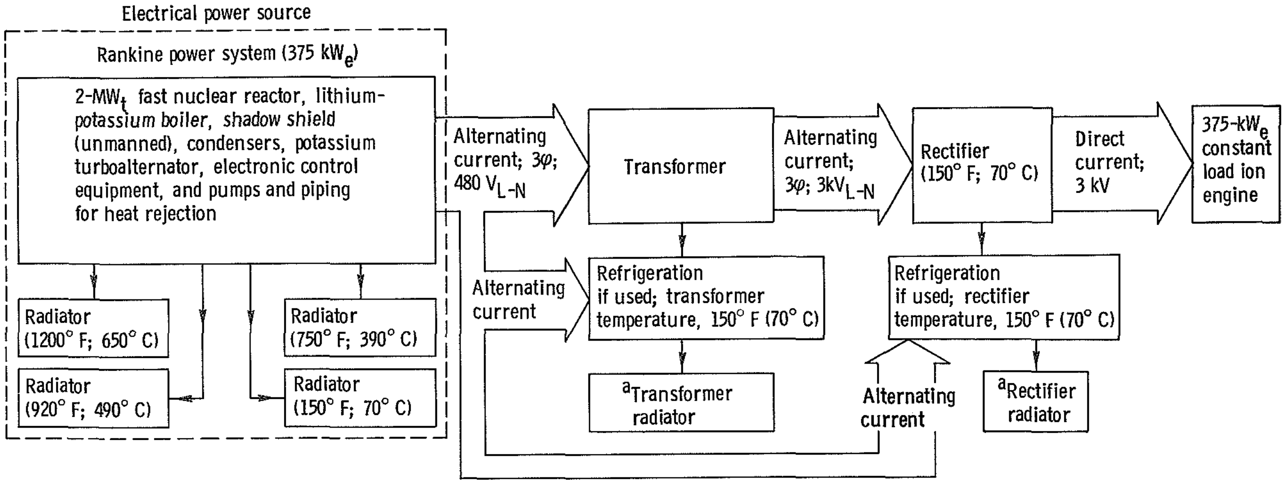
Of particular interest is the transformer design because of the flexibility in operating temperature, weight, and efficiency. Refrigeration as well as direct pumped fluid cooling to one of the four radiators were considered for both the transformer and rectifier. The results determine which heat exchanger combinations result in minimum overall system weight.

SYMBOLS

P_1	original rated power, kW
P_2	final rated power, kW
S_1	original specific weight, lb/kW (kg/kW)
S_2	final specific weight, lb/kW (kg/kW)
Δs	change in transformer specific weight, lb/kW (kg/kW)
T_{REF}	power conditioner operating temperature, ^{o}F (^{o}C)
T_{REJ}	power conditioning radiator temperature, ^{o}F (^{o}C)
$\Delta \eta$	change in transformer efficiency, percent
η_1	original efficiency, percent/100
η_2	final efficiency, percent/100
η_R	thermal efficiency, percent/100

ELECTRICAL POWER SOURCE

The electrical power source includes the 2-MW_t fast nuclear reactor, lithium-potassium boiler, potassium turboalternator, shadow shield, condensers, four radiators, and pumps. In other words, all the equipment necessary to provide electrical power from the homopolar alternator is included as the electrical power source. This



[a]Radiators become part of electrical power source radiators.

Figure 1. - Power system block diagram.

electrical power source is found to weigh 59.4 pounds per kW_e (27.0 kg/kW_e) (ref. 1). The overall power system block diagram is in figure 1. Inefficiencies in the power conditioning system reflect themselves rapidly as increased weight because the electrical power source must be increased to keep the output load constant.

ION THRUSTER LOAD

The ion thruster load is considered constant at 375 kW_e at unity power factor. Load voltages of ±3 kilovolts are required by the ion thruster. Circuit breakers, wiring, high-voltage insulation and arc suppression equipment, the ion engine controller, and ion engines are not included in the total system weight and are not included in this study.

REFRIGERATION

For this space application the most efficient refrigeration process is vapor evaporation. The thermal efficiency η_R equals the refrigerated power divided by the total power out and is approximated at 0.8 of the Carnot efficiency (ref. 2):

$$\eta_R = 0.8\left\{\frac{T_{REF} + 459.7}{T_{REJ} + 459.7}\right\}$$

In this report T_{REF} is the power conditioner operating temperature, while T_{REJ} is the heat rejection or radiator temperature. The specific weight is assumed to be $8/\eta_R$ pounds per kilowatt refrigerated (ref. 2).

The operating temperature of the rectifier is 150° F (70° C), while the operating temperature of the transformer is considered to be from 150° to 1200° F (70° to 650° C) at one of the four radiator temperatures. Various heat flow configurations for the power conditioning subsystems considered in this study are found in figure 2.

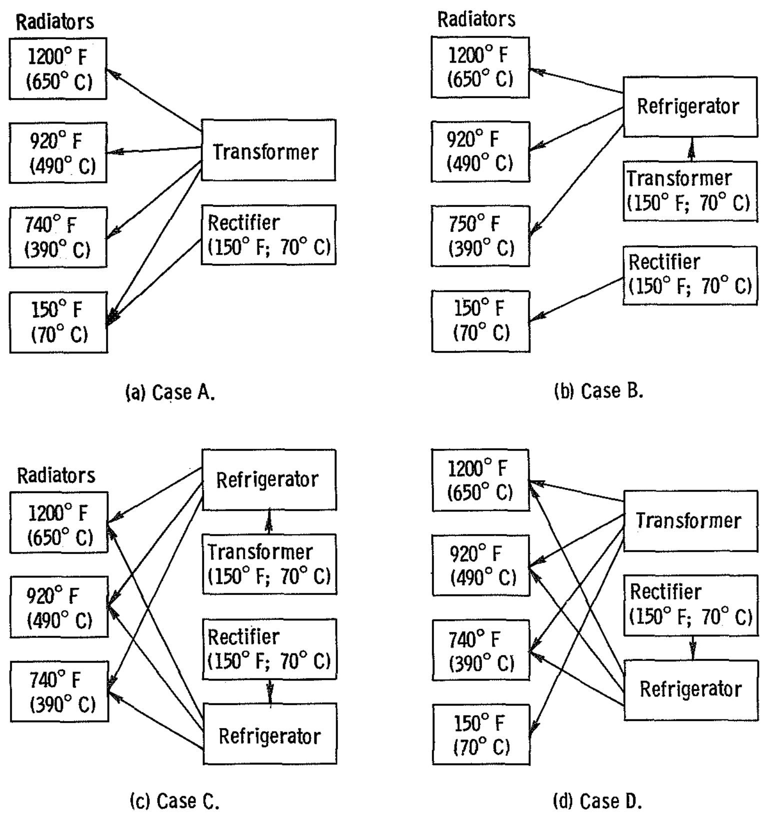


Figure 2. - Power conditioning heat flow diagrams.

Case A employs no refrigeration; the rectifier and its radiator are operated at 150° F (70° C), while the transformer and its radiator are operated at 150°, 740°, 920°, or 1200° F (70°, 390°, 490°, or 650° C). Both systems use a pumped coolant for heat rejection. In case B, the transformer is kept at 150° F (70° C) while refrigeration is used to reject the heat to a higher temperature transformer radiator. The rectifier rejects heat directly to the 150° F (70° C) radiator using a circulating coolant. Case C has both transformer and rectifier at 150° F (70° C) and refrigeration is used on each to reject the heat to a higher temperature radiator. Case D uses a pumped coolant for direct heat rejection of the transformer's heat. The rectifier is maintained at 150° F (70° C) by refrigeration which rejects heat to a higher temperature radiator.

HEAT REJECTION SYSTEM

The radiators, piping, and pumps make up the heat rejection system from the power conditioning equipment and/or power conditioning refrigerators. The heat rejection systems are considered to be additions to the four present power source heat rejection systems.

Specific weights for these rejection systems are 90 pounds per kW_t (40.9 kg/kW_t) at 150° F (70° C), 9.33 pounds per kW_t (4.25 kg/kW_t) at 740° F (390° C), 7.44 pounds per kW_t (3.38 kg/kW_t) at 920° F (490° C), and 2.27 pounds per kW_t (1.03 kg/kW_t) at 1200° F (650° C) (ref. 1).

RECTIFIER

Silicon diode rectifiers are employed to provide the required ±3 kilovolts direct current output. The rectifiers operate at 150° F (70° C) and have a total packaged specific weight of 0.142 pound per kW_e (0.065 kg/kW_e) and an efficiency of 99.50 percent (ref. 3). Additional shielding from radiation could be required if the rectifiers are located near the reactor.

The rectifier is considered in this study as a power conditioning subsystem separate from the transformer. It is included in this study to see if refrigeration is desirable on low temperature electronic power conditioning subsystems.

TRANSFORMER

The transformer is the other power conditioning unit considered in this study and is the device that is of most concern. In particular, the optimum operating temperature and tradeoff between efficiency and weight are needed for proper transformer selection for a space power application.

As information on transformer weight and efficiency as a function of temperature is acquired, scaling equations must be applied to yield values at the design power level. The specific weight varies as the power rating to the 1/4 power (ref. 4):

$$S_2 = S_1\left(\frac{P_1}{P_2}\right)^{1/4}$$

The percent loss of a transformer varies as power to the -1/4 power (ref. 4). It follows that the scaling equation for efficiency is

$$\eta_2 = \frac{1}{1 + \left(\frac{P_1}{P_2}\right)^{1/4} \frac{1 - \eta_1}{\eta_1}}$$

Care must be employed when scaling the previous transformer parameters so that about the same frequency and voltages are used in both cases, although frequency and voltage can also be scaled (ref. 4).

Figure 3 shows transformer efficiency as a function of temperature scaled to 375 kilovolt-amperes. The scaled developed SERT II power conditioning transformer is shown as a solid symbol. The other efficiencies have been calculated (refs. 3 and 5 to 7).

Figure 4 shows specific weight as a function of temperature for various calculated and developed transformers scaled to 375 kW_e (refs. 3 to 8). Any transformer designs in figures 3 and 4 that did not have a reasonable transformer efficiency to weight ratio for this electrical power source were discarded. The curves in figures 3 and 4 give the 375-kW_e transformer characteristics which were used in this study. Other more opti-

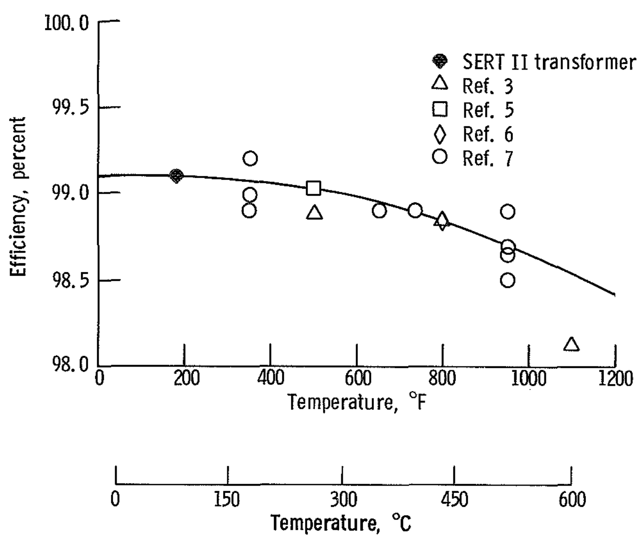


Figure 3. - Transformer efficiency as function of temperature scaled to 375 kilovolt-amperes at 1600 hertz with 3 to 5 kV_{L-N} on the secondary.

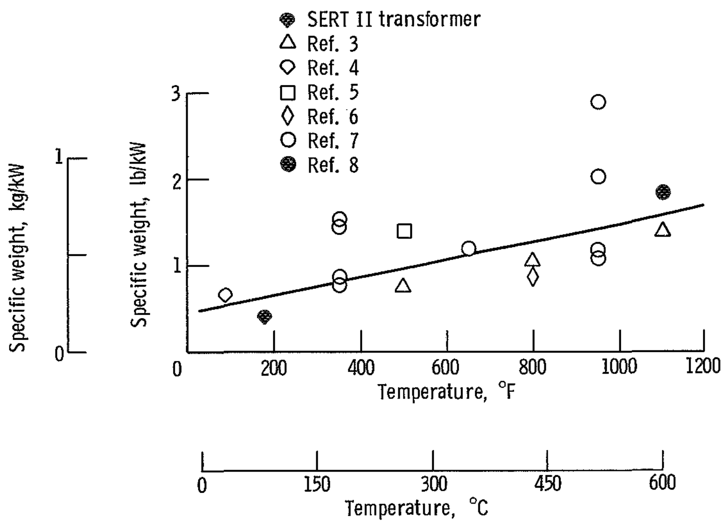


Figure 4. - Transformer specific weight as function of temperature scaled to 375 kilovolt-amperes at 1600 hertz with 3 to 5 kV_{L-N} on the secondary.

mistic curves were also tried but this did not appreciably alter system weight minimums and tradeoff ratios found later.

RESULTS AND CONCLUSIONS

Cases A and B of figure 2 represent the heat flow diagrams of the systems used in figure 5. In figure 5 total system weight is given as a function of transformer radiator temperature. The rectifier is maintained at 150° F (70° C) and this heat is rejected by a pumped coolant to the 150° F (70° C) radiator. A constant ion thruster load of 375 kW_e is assumed. The lower curve represents the 375 kW_e transformer directly rejecting its heat to the radiator by means of a pumped coolant. Minimum system weight occurs at a 740° F (390° C) transformer operating and radiating temperature. Figure 5 shows that at temperatures below 740° F (390° C) the transformer radiator weight becomes a large factor in the system weight, while above 740° F (390° C) a decreased transformer efficiency and increased specific weight make operation undesirable. In the upper curve the same transformer is operated at 150° F (70° C) with refrigeration used to reject the transformer heat to a higher temperature radiator.

Cases C and D of figure 2 represent the heat flow diagrams of the systems used in figure 6. Here total system weight is plotted against rectifier radiator temperature with transformer radiator temperature as a running parameter. A constant ion thruster load of 375-kW_e is assumed. The rectifier is operated at 150° F (70° C) and refrigeration is employed. The transformer is operated at 150° F (70° C) with refrigeration in case C while heat is directly rejected with a pumped coolant in case D. Cases C and D

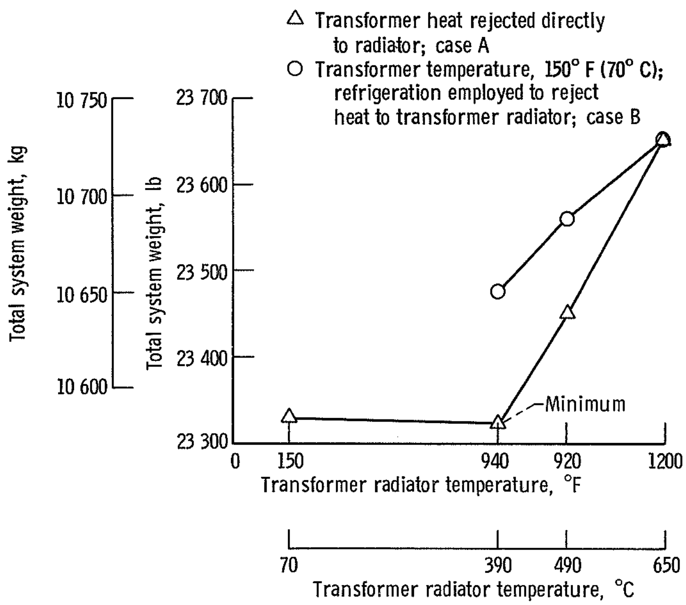


Figure 5. - Total system weight as function of transformer radiator temperature. 375-kW$_e$ load; rectifier at 150° F (70° C) directly radiating heat to 150° F (70° C) radiator.

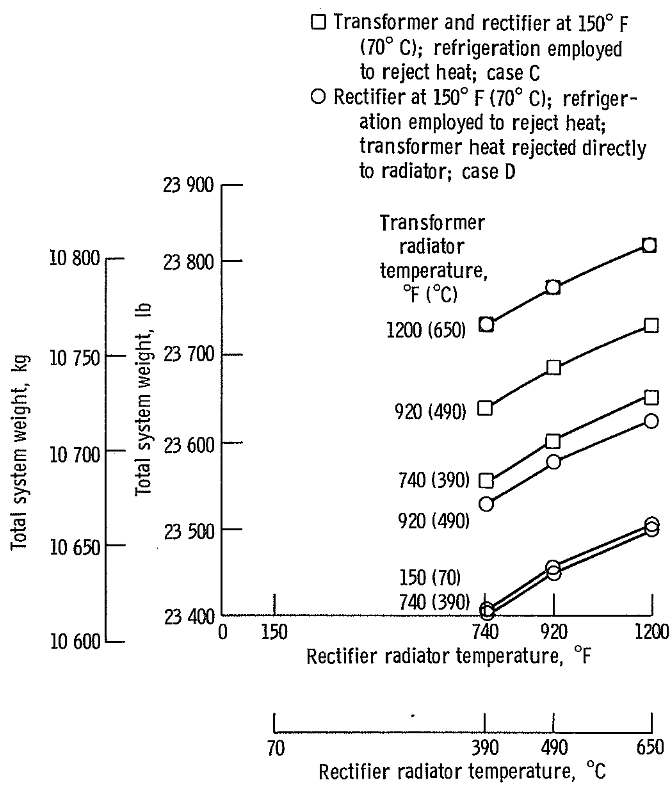


Figure 6. - Total system weight as function of rectifier radiator temperature. 375-kW$_e$ load; rectifier at 150° F (70° C) employing refrigeration to reject heat to radiator.

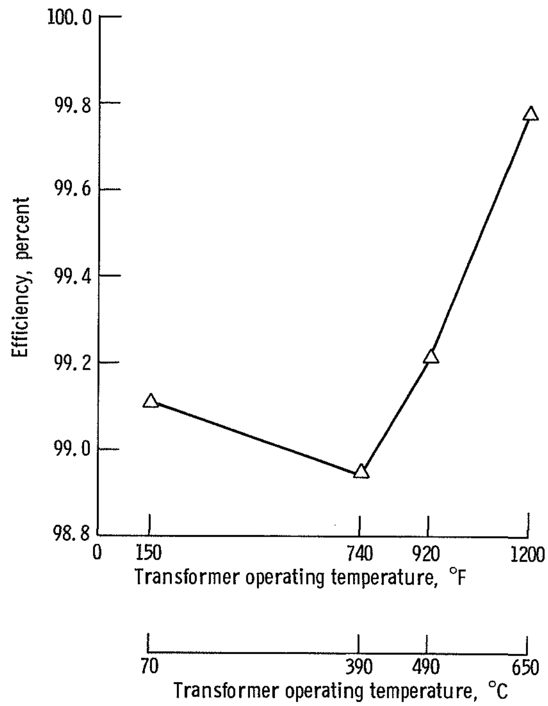


Figure 7. - Transformer efficiency required for minimum system weight of figure 5 as function of transformer operating or radiating temperature. 375-kW_e load; rectifier operating and radiating temperature, 150° F (70° C).

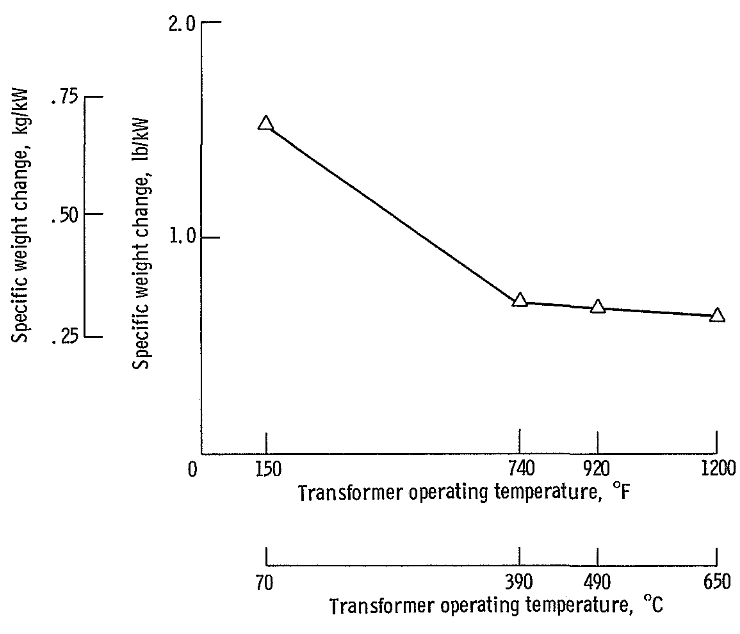


Figure 8. - Transformer specific weight change necessary to offset a percent change in transformer efficiency as function of temperature. 375-kW_e load; rectifier operating and radiating temperature, 150° F (70° C); transformer operating temperature equals radiating temperature.

in figure 6 are less desirable than case A in figure 5 because of the increased weight, complexity, and decreased reliability. Of these refrigerated versions the best seems to be with direct pumped heat rejection from the transformer at 740° F (390° C) and refrigeration employed only on the 150° F (70° C) rectifier.

In conclusion, the best power conditioning for 375 kW_e is when the rectifier operates at its radiator temperature of 150° F (70° C) and the transformer operates at its radiator temperature. The transformer operating temperature of 740° F (390° C) provides minimum total system weight as seen in figure 5.

With the rectifier operating and radiating at 150° F (70° C) while the transformer is also direct pumped cooled, the question arises as to what transformer efficiency is required at the other considered operating temperatures to yield the same total system weight as at the 740° F (390° C) minimum. The required equivalent efficiency as a function of transformer operating temperature for minimum system weight is shown in figure 7. The transformer specific weight of figure 4 is assumed. This curve requires high temperature transformers to be more efficient than lower temperature ones to be competitive; this seems physically to be a difficult matter.

Many transformer designs with various efficiencies and specific weights have been shown in figures 3 and 4. Heavier transformers are, in general, more efficient, whereas lighter versions are less efficient. To select the optimum transformer for this 375-kW_e Rankine power system the tradeoff between transformer specific weight and efficiency has to be known. In other words, how much weight will the system allow to be added to the transformer if the transformer efficiency is increased? Figure 8 indicates the change in transformer specific weight for a 1-percent change in transformer efficiency. This change results in a total system weight reduction assuming a 375-kW_e load. A base transformer efficiency between 98 and 99 percent is assumed. In transformer selection for this system, optimization of either transformer efficiency or specific weight should be performed until the tradeoff ratio ($\Delta S/\Delta \eta$) in figure 8 is obtained.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, July 22, 1970,
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